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Cross Linear Solar Concentration System for CSP

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Abstract

The novel solar concentration system, Cross linear (CL) system, with which a high cosine factor above 0.85 can be achieved through the year even in winter season and at high latitudes, has been invented by Tokyo Institute of Technology. Theoretical expression of the cosine factor for CL system can be given by cosine factor = sin δ{ cos ϕ (-cos μ) + sin ϕ sin μ) + cos δ cos ω(sin ϕ cos μ + cos ϕ sin μ), where δ, ϕ, μ, amd ω are solar declination, latitude, elevation angle of the reflection mirror, and hour angle, respectively. The value of tan μ corresponds to the ratio of the receiver height and mirror position distance from the receiver position for the receiver/mirror configuration of the CL concentration system. One simulation result for the CL system sample geometry (tan μ = 0.7, mirror length 1.5m, mirror number=13 in north side, and 2 in south side from the receiver) shows that we can get 7.7kWh/m^2/d for each mirror (as average) in December at 36.8°N latitude and 11.5 kWh/m^2/d in August, assuming DNI = 1.0kW/m^2 and collection efficiency = 1.0. Nearly the same result is obtained at high latitude of 40°N latitude. Thus, a higher cosine factor above 0.85 can be obtained in winter months even at the higher northern latitude. Also, the CL system can eliminate the end loss, and a comparison study shows that CL system can significantly increase the optical efficiency compared to Trough and LFR (Linear Fresnel Reflector system). Also, from the flux values above 100 kW/m^2 obtained by simulation for the CL system sample, it can be expected that a higher temperature around 600-700 °C can be reliably obtained and the air is heated up with a tubular receiver even in the winter season. With varying the parameters for CL system configuration, suitable solar concentration system with a high cosine factor could be designed depending on a wide temperature range of 300-700 °C. A joint collaboration between Japanese and Indian industries, institutes and universities has been launched to demonstrate and develop the CL system technology in Dec 2012.

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1. Introduction

The solar concentration systems, such as parabolic trough (Trough), linear Fresnel reflector (LFR) and power tower (PTower), the optical efficiency varies drastically with season and latitude, particularly in winter months [1-2]. Among these concentration systems, PTower has the higher optical efficiency in winter months, but lower in summer months, compared to Trough and LFR concentration system [1]. These variations with season and latitude result from the cosine factor change in the optical concentration systems. For LFR and trough systems, the optical efficiency of horizontally rotating mirrors suffers from the cosine factor due to the north-south inclination of the sun. The optical efficiency becomes worse when the solar plant is constructed in geographic zones with high latitudes. Also, this cosine effect is limited by the end loss, which comes from the reflected light going beyond the end of the receiver due to the inclination of the sun in the direction of the axis of the receiver. Thus, the output of the solar plant based on conventional concentration systems is greatly lower during the winter months than that during the summer months [1-3]. These effects are called “declination penalties”; the effect of the declination penalties can be felt right from latitude N20^{o} or so, and becomes more important as the latitude increases [2]. For geographic zones with latitude over 40°, the installation of a horizontally mounted concentrator is not recommended because the penalties are so serious [4]. It is proposed that large-scale solar fields be installed in North African countries, and then long distance power transmission lines be drawn to transport the generated power to Europe [5]. But the declination penalties are very significant because North African regions near Europe are of latitude near 36.8^{o}N. The innovation in the concentration system to guarantee the high cosine effect in winter months and/or in high-latitude region is of great importance to the development of CSP technology.

On the other hand, large scale and economically feasible thermal energy storages play an important role in the development of the future energy grid using solar energy. To achieve the high performance of thermal storage, the temperature of working fluid should be kept at higher than 600°C. For the higher cost performance of the thermal storage, the higher temperature above 600^{o}C of thermal fluids is required to reduce the thermal storage tank volume. To date, the solar concentration system which gives the high temperature above 600^{o}C is the tower-type system. For the linear concentration system, the temperature of the trough system using the oil is around 400^{o}C due to a limitation coming from the heat instability of the oil, but using the molten salt or steam instead of the oil, the higher temperature can be raised around 500^{o}C. There is Linear Fresnel system as another linear concentration system, but its temperature is around 550^{o}C for using steam. Thus, with the linear concentration systems, we can’t get the higher temperature above 600^{o}C. Moreover, for the linear concentration systems, the problems for the trough system is that a very long receiver line absorbing the collected sun light is needed, because there is a limitation in the mirror area used for the unit receiver line length.

To address these issues on the declination penalties and the high temperature solar thermal collection above the temperature of 600^{o}C, a new solar concentration system, CL system, has been invented by Tokyo Institute of Technology. This paper describes the optical principle of CL system and the simulation results for the improvement of the declination penalties by CL system.

2. Cross Linear concentration system

Figure 1 shows the sketch of the CL-system which consists of linear mirror lines and receiver lines. The both lines are crossed each other at right angles; the mirror lines are aligned on a north-south axis, and the receiver lines, on an east-west axis.

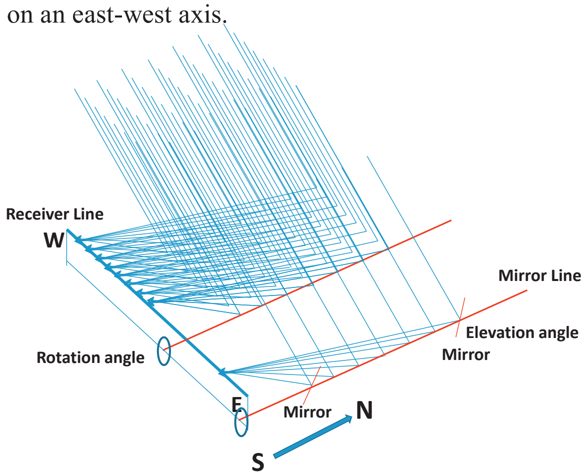

Fig. 1 Conceptual sketch of CL-system

Figure 2 shows the solar concentration concept of the CL-system using several mirrors (three mirrors are shown in Fig. 2) which can be operated by adjusting the rotation and elevation angles. The three mirrors 1,2, and 3 are placed on the same OO' axis (North-South), and can be rotated along the axis. Each mirror situates at the center of the horizontal line and celestial sphere. All the incidents are in the same direction for each mirror, therefore apparently we may say that we could concentrate the sun light with these mirrors by using a different elevation angles for each mirror at a nearly the same rotation angle. Exactly saying, we have to control the rotation angle for each mirror, because the rotation angles are different for each mirror position, but several mirrors located at some distance from receiver can be rotated together within a required error range; we can operate several mirrors within some error range by adaptation of the same rotation angle for each mirrors. Anyway, we can achieve the solar concentration by the solar concentration concept given by Fig.2, where the rotation angle and elevation angle of the

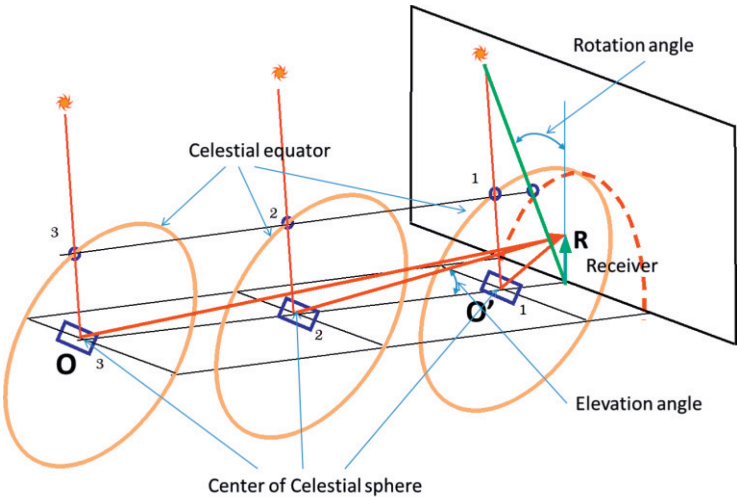

Fig. 2 Solar concentration concept of CL system using multi mirrors by operating rotation and elevation angles

mirror are controlled; we can track the sun and make a solar concentration by adjusting the (1) rotation angle of the north-south axis and (2) elevation angle. Also, we could reduce the number of tracking axes from two, which are needed for the tower heliostat, to a small number of axes below 1.05 (five mirrors controlled with the same rotation angle).

Figure 3 shows geocentric frame for understanding CL concentration system. Circle a is the celestial sphere. N, W, S and E indicate north, west, south and east, respectively. N' is the celestial north pole. Circle FEGW and circle NWSE are celestial equator and horizontal line. Point O, where a mirror is placed, is center of the horizontal line NWSE, respectively. The Sun light from the point S' on the celestial equator FEGW reaches the point O and reflected by the mirror. In the CL system, the reflected light goes toward the receiver R, which is placed on the north-south axes. The $\overrightarrow{OS'}$ and $\overrightarrow{OR}$ are direction vectors pointing toward the positions of the Sun and the receiver R, respectively. The corresponding angles for $\overrightarrow{OS'}$ are Azimuthal angles (A) and solar altitude (α). The Azimuthal angles (A) are measured clockwise on the horizontal plane, from the north-pointing coordinate axis to the projection of the sun's central ray. The corresponding angles for $\overrightarrow{OR}$ are elevation angles (μ) from the ground level at the mirror position O. In the CL concentration system, the receiver is just on the line of the mirror line which is perpendicular to the receiver line placed in the east-west direction. Therefore, only the one angle of elevation angles (μ) is given for the direction vector $\overrightarrow{OR}$. The sun's declination angle, which is limited to the range of $-23.45 \leq \delta \leq 23.45$, is indicated by δ in Fig. 1. The hour angle ω varies between -180 and 180^o, with $\omega = 0$ at solar noon and $\omega > 0$ after noon. The latitude angle is shown in Fig. 1 by ϕ.

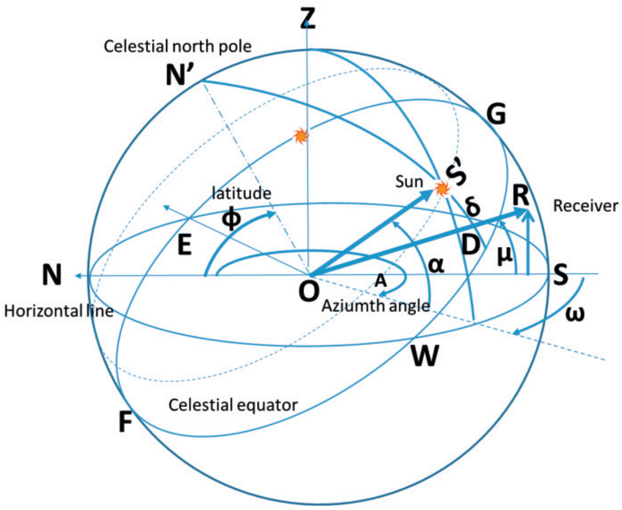

Fig.3 Ray tracing of the sun light for solar concentration by the CL-system in the global optics configuration

The direction vector $\overrightarrow{OS'}$ in terms of α and A in the geocentric coordinate frame is related to vector components S_z, S_e, S_n in a rectangular Cartesian frame (Fig. 1) (subscripts z, e, and n denote the z, e, and n axes toward zenith, east, and north, respectively), and they are given by

$$S_z = \sin \alpha$$

$$S_e = \cos\alpha \sin A \quad (1)$$
$$S_n = \cos\alpha \cos A$$

The vector components of the unit vector of the direction vector $\overrightarrow{OR}$ are given by

$$Rz = \sin\mu,$$
$$Re = 0, \quad (2)$$
$$Rn = -\cos\mu.$$

The cosine factor for each reflection mirror is given by

$$\text{CosEffct} = \sin(\text{arch}\sin\{(\overrightarrow{OS'} \cdot \overrightarrow{OR}) / |\overrightarrow{OS'}| \cdot |\overrightarrow{OR}|)/2\}) \quad (3),$$

where $\overrightarrow{OS'} \cdot \overrightarrow{OR}$ is the scalar product, and $|\overrightarrow{OS'}|$ and $|\overrightarrow{OR}|$ are lengths of the vectors. They are written by

$$\overrightarrow{OS'} \cdot \overrightarrow{OR} = \sin\alpha \sin\mu + \cos\alpha \cos A(-\cos\mu) \quad (4),$$

and

$$|\overrightarrow{OS'}| \cdot |\overrightarrow{OR}| = 1 \quad (5).$$

Since $\sin\alpha$ and $\cos\alpha \cos A$ in eq. 4 can be given by

$$\sin\alpha = \sin\delta \sin\phi + \cos\delta \cos\omega \cos\phi \quad (6)$$
$$\cos\alpha \cos A = \sin\delta \cos\phi - \cos\delta \cos\omega \sin\phi \quad (7),$$

the eq.4 can be rewritten by

$$\text{CosEffct} = \sin\delta\{\cos\phi(-\cos\mu) + \sin\phi \sin\mu) + \cos\delta \cos\omega(\sin\phi \cos\mu + \cos\phi \sin\mu) \quad (8).$$

Eq. 8 shows how cosine effect varies depending on latitude, declination angle, hour angle, and tan μ. The value of tan μ corresponds to the ratio of the receiver height and mirror position distance from the receiver potion for the receiver/mirror configuration of the CL concentration system.

Figure 4 shows the relationship between cosine factor and declination angle at various latitude values from 20^{o} to 40^{o}N at solar time =10h and for tan μ = 1.0. From Fig.4, it can be seen that the cosine factor increases with an increase in the latitude. This is very interesting result, and is fully reverse relationship occurred in the Trough and LFR. As described above in the section of introduction, one of the big problems in the existing concentration systems of Trough and LFE is the lower concentration efficiency (lower cosine factor) in the winter months [1-3]. And this reduction characteristics increase with an increase in latitude. Considering from those findings, it could be said that the problem on the cosine losses enhanced by the “declination penalties” occurring in Trough and LFR seems to be dissolved by applying the CL system. For the latitude 36.8^{o}N, the cosine effect value is 0.91 at summer solstice, and increases gradually with decrease in declination angle and attains 0.97 at winter solstice. For the latitude 45^{o}N, it is 0.95 at summer solstice, and becomes 0.97 at winter solstice. Thus, the larger the latitude, the larger is the cosine factor. And these cosine values are above 0.9 and coming to nearly 1.0, indicating that the concentration efficiency in terms of cosine effect becomes nearly the maximum.

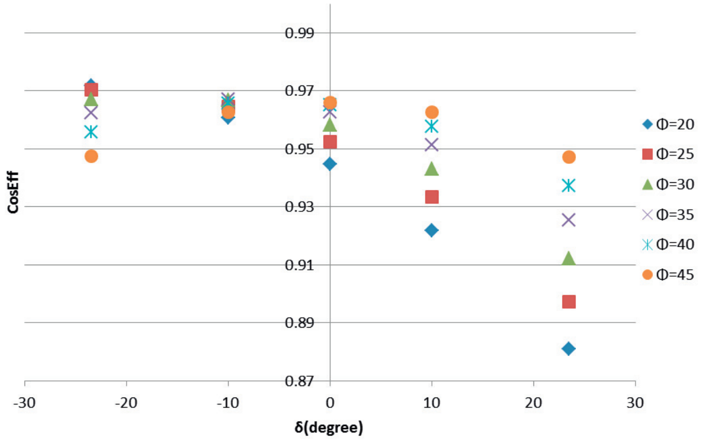

Fig. 4 Cosine effect variation with declination angles for various latitude values

3. Comparison on cosine effect between Cross Linear and Trough during winter solstice

Figure 5 shows the simulation results on the comparison of solar concentration efficiency (cosine factor) between CL and Trough (Curve A; CL, B; Trough). The simulation was carried out by assuming that the site is Almeria in Spain (latitude 36.8 N and the date is winter solstice. For the calculation of cosine factor in Fig. 5, we have used eq.8 for CL system and the equation in reference [6] for the calculation of cosine factor of Trough system. For both of CL system and Trough system, those are aligned on a North-South axis. The shadowing loss factor for Trough system was estimated from the eq.(4.3) given in the literature [7]. The same shadowing loss factor was applied for the calculation of the CL system, assuming that the same shadowing effect takes place. This assumption is reasonable for the same ratio of the aperture mirror length and the distance between mirror rows, because the mirrors surfaces face to the sun light direction by rotating the north-south axis in both of the Trough and CL systems. For the calculation of the CL system, the mirror ray-out, the ratio of the receiver height and the distance between the receiver position and mirror position, and mirror/mirror distance were designed to eliminate the blocking effect during the operation. In this sample geometry, 15 number mirrors (width1.8m x length 1.5m) are arrayed on the same mirror line with North-South direction (one mirror line; mirror numbers are from one to 15). The mirrors from 11 to 15 are placed on the same mirror line with an inclined angle of 15^{o}. For an equivalent evaluation, the same mirror area was adopted between CL and Trough systems.

As can be seen from Fig. 5, the cosine factor of TR (Curve B) reaches peak value at 9:30am, significantly decreases, and then increases back to peak value at 2:30pm. In case of CL system (Curve A), the cosine factor almost keeps constant as it reaches peak value from 9:30am to 2:30pm during sunshine duration. The cosine factor for Trough system is lower than that for the CL system from 8am to 4pm during sunshine duration. This difference comes from the fact that the cosine factor for the CL system can be determined by eq. 8, which gives higher values for the higher latitude. On the other hand, the cosine factor for the Trough system decreases with an increase in the latitude. Thus, the higher value of the CL system in winter season (large minus declination value) is the unique characteristic for the CL system.

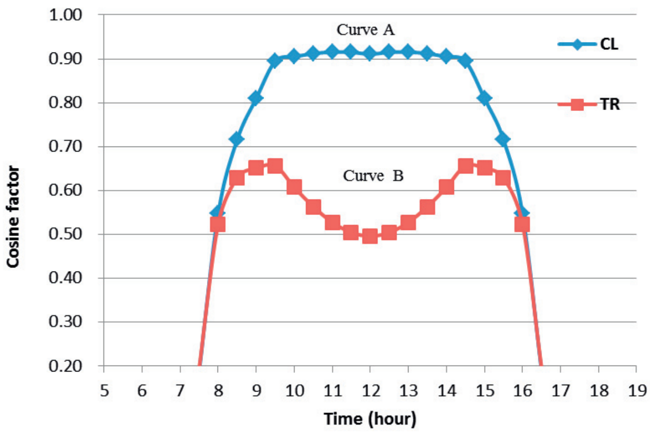

Fig. 5 Comparison of cosine factor between CL and trough systems in winter solstice at Almeria in Spain (Curve A; CL, B; Trough)

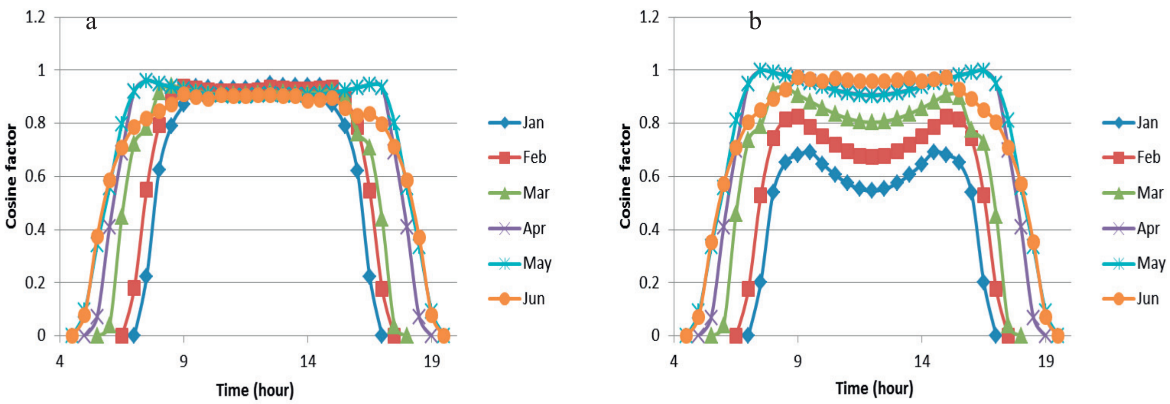

Fig. 6 Dependence of cosine effect on time in daytime (solar time) for CL and trough systems at Almeria (Spain), (a) January; (b) February; (c) March; (d) April; (e) May; (f) June.

Figure 6 displays the calculation results, which describes the dependence of cosine factor on time in daytime from Jan to Jun for CL and Trough systems at Almeria in Spain. The calculation parameters are the same as Fig.5. For the CL system (Fig. 6 a), once it reaches peak top, the value of cosine factor keeps constant with time until it drops. There is no obvious difference in the value of cosine factor among different months. The difference in the cosine factor among different months is only the solar collection time period; it is shorter in winter months than in summer months. For Trough system (Fig. 6 b), the cosine factor is almost constant in May and June, but it significantly drops in April, March, February and January and reaches peak bottom at 12 clock. Comparing CL system (Fig. 6a) and Trough system (Fig.

6b), it is obvious that the cosine factor of Trough system is greatly influenced by month (due to change in declination angle). The CL system can keep the value of cosine factor as high as 0.95 even in winter months. When compared to the conventional systems which set the heliostat in the north field of tower system, the cosine factor of some of heliostats can't keep the cosine factor above 0.8 all the time. Therefore, the advantage of CL solar collection system is prominent.

4. Constant cosine factor of CL system throughout the year

As described above, the cosine factor of CL system can be kept constant throughout the year (Figs 6 a and b). For calculation of the simulation, we have used the sample design of the plants for CL and Trough systems. The simulation results on Figs.6 a and b indicates that the CL system will practically collect the sun light at a high cosine factor throughout the year. However, the totally collectable amount of the solar energy is the function of the sunshine duration (hours) in a day (month or year) and cosine factor. Figure 7 shows the comparison of the daily collected solar energy (primary vertical axis) and daily averaged cosine factor (secondary vertical axis) during sunshine duration of CL system and Trough system for each month in a year at Almeria (latitude 36.8° N) in Spain. To see more clearly how the collected solar energy varies during the winter season, the plot of data starts with July; the data in the winter seasons are plotted around middle of the horizontal axis in Fig.7. The calculation parameters are the same as aforementioned in Figs 5-6. The daily average cosine factor in the secondary vertical axis of Fig.7 means the average cosine factor during the sunshine duration in a day (DavAv-cosine factor). As shown in Fig. 7, DayAv-cosine factor of CL system does not vary much with month in a year, and keeps almost the same value greater than 0.75. On the other hand, the DayAv-cosine factor of Trough system changes dramatically, which first drops as winter months come, and then goes up when summer months come. Thus, the lower efficiency of Trough system in the winter months can be clearly seen, when looked at the daily efficiency as a day operation.

The collected solar energy per day for CL and Trough systems, assuming that the DNI=1.0kW/m^2 and mirror reflectivity =1.0, is also given in Fig. 7. The collected solar energy per day of both CL system and Trough system shows the same trend that the collected energy per day first decreases and then increases. For Trough system, the drop of the collected solar energy is due to the fall of the cosine factor in winter month. But for the CL system, even the cosine factor keeps almost the same, the collected energy per day greatly decreases. This is because the collected solar energy depends on both the cosine factor and the sunlight duration. In winter season, the sunlight duration becomes significantly shorter than that in summer season. Therefore, the CL system can collect the maximum amount of solar energy even in winter seasons at high latitude.

Cosine losses occur whenever a collector (mirror) is not oriented perpendicular to the rays of direct radiation. A perpendicular orientation would allow the collector to absorb the maximum direct resource. At any other orientation, a fraction of that maximum energy is available. The fraction is proportional to the cosine of the angle between the collector and direct rays. Linear focusing CSP plants require high direct solar resource like all concentrating technologies. In addition, the fact that they only track the sun in one axis means that cosine losses impact on their performance. The size of the concentrators and the fact that they only track in a single axis dictate that the tracking axis be horizontal. This means that cosine losses will be greatest at midday when the trackers are unable to tilt the reflectors toward the sun for existing linear focussing system. Midday is also the time of most direct resource. Because of this sensitivity to sun height, linear focusing concentrators will perform significantly better in the summer than in the winter. It also makes linear concentrators less effective at higher latitudes. In these situations for the existing linear concentration systems, our new line concentration system of CL system, as seen in Figs. 5-7, doesn't suffer from cosine losses. This can be explained from eq.8, which functions to increase the cosine factor (meaning an effectively reflectable configuration of the mirror position) with an increase of latitude and declination angles.

This kind of constant high cosine factor throughout the year seems to give a very reliable operation for getting a high temperature around 650°C. The CL system would be applied for getting a higher temperature of steam and some thermal fluid for power generation and effective heat storage system.

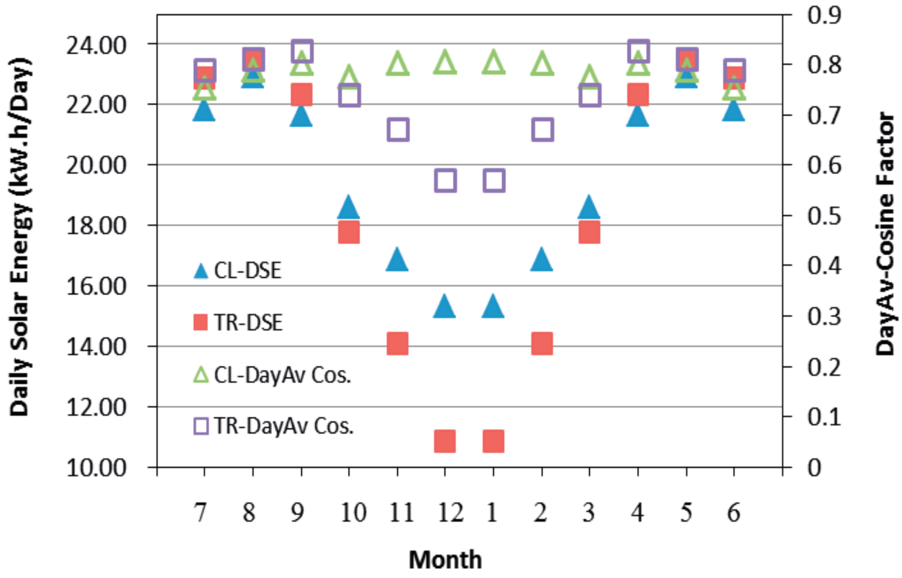

Fig. 7 Comparison of daily collected solar energy and day average cosine factor during sunshine duration of CL system and Trough system for each month in a year at Almeria in Spain (solid triangles represent daily collected solar energy of CL system; solid rectangles daily collected solar energy of Trough system; open triangles cosine factor of CL system; open rectangles cosine factor of Trough system).

5. Cosine factor for each mirror

Fig. 8 shows the cosine factor variation for 15 numbers of mirrors in the sample design of the plant for CL system at spring solstice at Almeria. The mirror number axis is in right of bottom plane of Fig.8. The cosine factor of each mirror is given by vertical axis. The horizontal axis in Fig.8 indicates the hours solar time) in a day. Three mirrors are placed in the south side and 12 mirrors in north side from the receiver. As can be seen here, all the mirrors can get the cosine factor above 0.8 from 7am to 5pm (nearly every time and every mirror). When compared to the conventional systems which set the heliostat in the north field of tower system, the cosine factor of some of heliostats can't keep the cosine factor above 0.8 every time. However, for CL system, every mirror has the cosine factor above 0.8, indicating that CL-system with north field ray-out of the heliostat (mirror) would have a higher solar collection efficiency than other tower systems such as e-Solar system with the north field ray-put. Thus it seems that the CL-system is the highest solar collection efficiency among the existing concentration systems.

In the calculation of the simulation for comparison between Trough and CL systems, we have not taken into account of the end loss for Trough system. For CL-system, no end loss takes place, because every light reflected by the mirrors is perpendicularly passed toward the receiver.

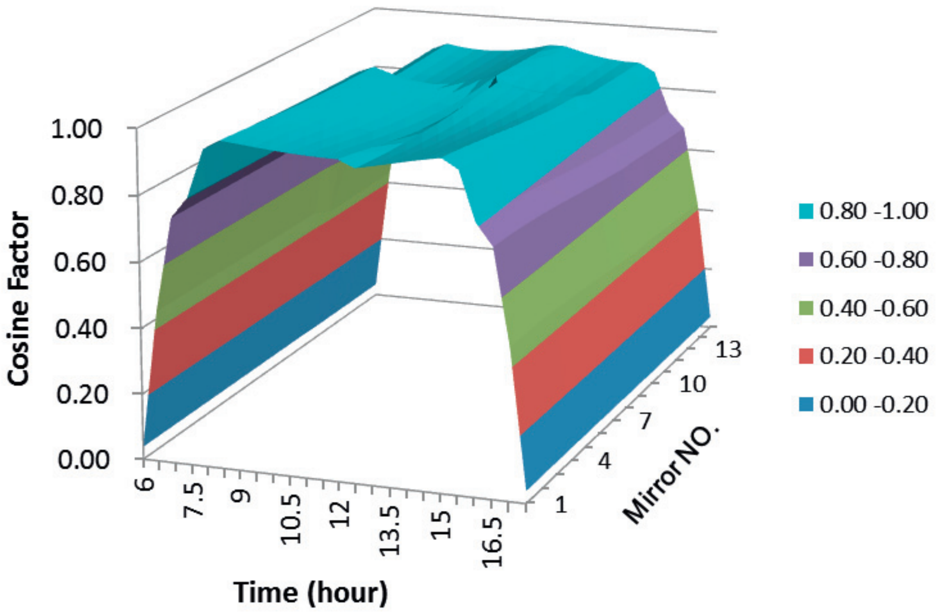

Fig. 8 Daily cosine factor of each mirror for CL system (Mirror 1-15) in March at Almeria at Spain (latitude 36.8 °N).

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